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Fire Detectors in Underground Mines

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By Charles D. Litton

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FIRE DETECTORS IN UNDERGROUND MINES

by

Charles D. Litton[1]

ABSTRACT

An overview of state-of-the-art technology in fire detectors is presented by the Bureau of Mines regarding their use in the mining industry. Detectors are categorized according to the characteristics of a fire to which they respond. Operating principles of the various detectors, their application, and the advantages and disadvantages of each are discussed.

INTRODUCTION

When a fire or explosion occurs in a mine, detection must be rapid enough that corrective action can be taken to prevent the loss of life and the devastation of all or parts of the mine. Also, the detector and detection system should be as reliable as possible; they should have a minimum of false alarms and maintenance. This Bureau of Mines paper discusses the types of fire detectors that are available, their general applicability and reliability, and touches on current research efforts in the area of fire detection.

OPERATIONAL CHARACTERISTICS OF CONVENTIONAL FIRE DETECTORS

Fire detectors respond to some physical or chemical characteristic of the fire itself, or to some change in the environmental conditions resulting from a fire. Fire detectors are generally categorized as follows:

1. Thermal sensors (sensors that respond in some manner to the change or rate of change of the ambient temperature),

2. Aerodynamic sensors (sensors that respond to the change in pressure or the direction of ventilation flow),

3. Optical sensors (sensors that respond to the radiant energy emitted by a fire or explosion), and

4. Products-of-combustion sensors (sensors that respond to some product of the combustion process).

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Thermal and Aerodynamic Sensors

Thermal and aerodynamic sensors respond to environmental changes produced by the presence of a fire. Thermal sensors detect an increase in air temperature and actuate an alarm that signals the presence of a fire condition. Various types of thermal sensors are commercially available.

Thermocouples are perhaps the most widely used sensors in this category. (A thermocouple is a bimetallic junction that generates an emf when heated.) They are fairly rugged and suffer no adverse affects from humidity or convective cooling owing to the ventilation flow. Sensitivity is adequate, and reliability is fairly high.

Another thermal sensor is the thermoresistive type, such as resistance thermometers and thermistors. These sensors change their resistance as the temperature increases. In particular, thermistors appear to offer some potential as thermal fire sensors. However, these devices should be maintained at a fairly constant humidity and should not be subjected to excessive changes in the ventilation flow. These factors can adversely affect the sensitivity and, hence, the reliability of the sensor.

Other types of thermal sensors include (1) line-type heat sensors, which produce an alarm when heated; (2) fixed-temperature sensors made of temperature-sensitive materials, which expand, bend, or fuse to produce an alarm; (3) rate-of-temperature rise sensors, which respond to increasing temperature changes; and (4) pressurized heat-sensitive plastic tubes, which melt at a given temperature resulting in a loss of pressure.

Line-type heat sensors are perhaps more versatile than point-type heat sensors, such as thermocouples, because they form a continuous heat sensor over the entire area to be covered. A small resistor is placed between the wires at one end, and the current flow is monitored. When the current increases, an alarm is given. Additionally, when no current flows, this condition signals a break in the wiring.

Fixed-temperature sensors, like thermocouples and thermistors, are localized temperature sensors, but they suffer from the additional constraint that a specific temperature must be reached before an alarm can be actuated.

Rate-of-temperature rise sensors generally respond only to large changes in temperature per unit time. However, some sensors of this type have built-in compensation for the rate of temperature change and offer some capability for use in detecting small fires or slowly developing fires.

Heat-sensitive plastic tubes is another type of thermal sensor. The tubes are pressurized with air; an increase in temperature melts the tubing, resulting in the loss of pressure. This pressure loss is sensed and an alarm is actuated.

Generally, thermal sensors are fairly reliable, but time response can be quite long (several minutes). For example, if a fire occurred immediately adjacent to a thermal sensor, it would respond rapidly. But, if a fire occurred far removed from a thermal sensor, the ventilation flow would be required to carry the warm air to the sensor. Along the way, the air would cool (depending on the intensity of the fire and ventilation flow), and the time response could be too long to initiate any corrective action.

Maintenance of a thermal-sensing system should be fairly straightforward, but the time spent on maintenance can be lengthy, depending on the number of sensors and the electronics associated with an individual network. These systems, or components to build a total system, are commercially available.

In addition to a change in the ambient temperature resulting from the presence of a fire, changes in the static pressure and the ventilation flow may also occur. Significant pressure changes are usually the result of explosions rather than fires. Therefore, pressure-sensitive detectors (aerodynamic sensors) are used primarily to detect a propagating explosion and to actuate some extinguishing agent to arrest the explosion before it can devastate the entire mine. In some instances, pressure-sensitive switches can be used to remotely close fire doors at key points within a mine.

If the fire is large enough, the ventilation flow can be drastically affected, often causing a reversal in the direction of flow. Anemometers or velocimeters could be used to sense extreme changes in flow conditions should other fire protection measures fail. Such backup systems have not found widespread application because the degree of protection is marginal at best.

Optical Sensors

When a fire or an explosion occurs, a tremendous amount of energy is released in the form of electromagnetic radiation. This radiated energy can be either in the form of selective molecular radiation or graybody continuum radiation. The selective radiation occurs when gaseous species within the flame, which have been initially excited to higher energy levels owing to the intense heat, lose their energy in returning to a lower energy state. The energy is selective, or discrete, because it can be emitted only at discrete wavelengths characteristic of the internal energy structure of the molecule. Examples of selective emitters from fires or explosions and their associated emission wavelengths include the following: OH at 0.28 and 0.31 μm; CH at 0.43 μm; C_2 at 0.51 μm; H_2O at 1.87, 2.7, and 6.6 μm; and CO_2 at 2.7 and 4.3 μm.

Graybody radiant energy is energy that is emitted due to the temperature of hot objects within the flame such as dust or soot. Graybody radiation is responsible for the characteristic orange-yellow color associated with a fire. This type of radiation does not show up at discrete wavelengths but is emitted throughout the entire region of the electromagnetic spectrum. The total intensity of this radiation varies with the temperature of the emitting body. Also, there is at every increasing temperature value an associated peak in the intensity distribution at decreasingly shorter wavelengths. For example, for a hot object at 500° C, the peak in the continuum radiation occurs at 3.75 μm, but at 1,000° C, the peak occurs at a wavelength of 2.28 μm.

Optical sensors are designed to detect either selective radiation or graybody radiation or both. They are usually classified according to the wavelength region of the spectrum to which they are most sensitive. Ultraviolet sensors respond to energy emitted between 0.18 and 0.4 μm; visible sensors respond to energy between 0.4 and 0.75 μm; and infrared detectors respond to energy between 0.75 and 20.0 μm. Optical sensors are generally used for fire or explosion detection in situations where rapid response is a primary consideration. Their time responses range from a few picoseconds or lower to several milliseconds and are therefore ideally suited for applications needing quick response times. They are essentially line-of-sight devices; therefore, their application is somewhat limited to small-area coverage, where the probability of the occurrence of a fire or explosion is greater than in other areas.

Optical sensors may be further categorized according to their principle of operation:

1. Photoemissive.--This type of optical sensor utilizes a light-sensitive material that gives off electrons when radiation is incident upon it. The movement of these electrons to an electrode produces a current proportional to the intensity of the incident radiation. These types of devices are generally used in the ultraviolet and visible regions of the spectrum.

2. Photovoltaic.--This type of sensor is a semiconductor that produces a voltage proportional to the intensity of the incident radiation. This type of sensor is generally used in the visible and near infrared regions of the spectrum.

3. Photoconductive.--This type of sensor is a semiconductor material that changes its electrical conductivity with incident radiation. It is generally used in the visible and infrared regions of the spectrum.

Optical sensors are commercially available at reasonable costs. They are used widely for fire protection where rapid response is required. Applications include detectors for methane-air ignitions, coal dust-and-air explosions, fuel-storage or flammable-liquid storage areas, and large mobile equipment, etc. Optical sensors offer potential for the detection of hot and cold spots within mines and for detecting overheated machinery or overheated conveyor-belt idlers. Because of the size of most underground mines, optical sensors are inadequate as a general fire detector for complete mine coverage; their greatest utility is for protection in high-risk areas or as protection for large equipment, where loss in terms of lives and capital could be substantial.

Products-of-Combustion Detectors

In addition to radiant energy produced by a fire or explosion, gaseous products and large quantities of submicrometer particles are generated. Products-of-combustion (POC) detectors are designed to detect the presence of these gases or particles, which are not normally present in large quantities in mine atmospheres. They are rarely used for detecting explosions but offer great potential for detecting fires.

Gaseous Products-of-Combustion Detectors

Perhaps the best known gas detectors are those that detect the presence of carbon monoxide (CO). There are several different types of CO detectors, each of which operates on a different principle.

1. Catalytic oxidation.--A catalytic material, such as Hopcalite, reacts with the CO to exothermically produce a change in the temperature of the catalytic material, which is proportional to the change in CO concentrations.

2. Optical techniques.--Carbon monoxide will absorb radiant energy at discrete wavelengths, the total absorption being related to the CO concentration. For these types of detectors, a light source, absorption cell, and detector are used. Without CO present, the light source provides a constant signal to the detector. When CO enters the absorption cell, this signal is attenuated, the total attenuation being related to the CO concentration.

3. Electrochemical cells.--A special electrode is located within an electrolyte. When CO is present in the air passing over the electrolyte, a chemical reaction at the sensing electrode generates a current proportional to the CO concentration.

4. Semiconductors.--A semiconducting element changes its resistance in the presence of CO. The change in resistance is related to the CO concentration.

5. Chemical absorbents.--A chemical mixture, such as iodine pentoxide and selenium dioxide, changes color in the presence of CO. Depending upon the sampling instrument and its configuration, either the length of the color change or its intensity is proportional to the CO concentration.

Carbon monoxide detectors have found their greatest utility as fire detectors in coal mines, where a principle product of spontaneously heating or rapidly burning coal is CO. Sensitivity of 1 ppm or less are readily achievable with off-the-shelf instrumentation. However, some of these instruments are sensitive to other gases such as oxides of nitrogen, methane, and heavy hydrocarbons. Small quantities of these interfering gases produce signals that indicate erroneous levels of CO. Past and current research efforts by the Bureau have resulted in instruments and techniques that tend to minimize these interferences, while maintaining high CO sensitivity.

Since carbon dioxide (CO_2) is a primary product of the combustion process, its detection can also be used to signal the presence of a fire. The major technique for measuring CO_2 concentration utilizes the optical absorption properties of the molecule in a manner similar to that described for CO. Current instrumentation based upon this principle are fairly expensive and difficult to adapt to underground use because of their complexity. Nonetheless, there are instruments available for use underground.

Particulate Products-of-Combustion Detectors

In addition to CO, CO_2, and other gases that may be produced by the combustion process, large quantities of submicrometer particles are expelled. These particles are initially so small (<0.10 μm in diameter) that they are invisible to the human eye. As the intensity of the combustion process increases, larger and larger concentrations of these particles are produced. At these high concentrations coagulation occurs more rapidly, and the particles tend to grow in size producing visible smoke. Particulate fire detectors are designed to detect either invisible or visible particle concentrations and to actuate an alarm. There are basically four types of devices that can be used for particulate detection.

1. Condensation nuclei counters.--Particles are introduced into a region of high supersaturation (cloud chamber technique). The particles serve as nucleation centers for the saturated water vapor. As the water condenses upon the particles, the size increases to a point (~1.0 μm) where the number concentration can be measured optically.

2. Surface-ionization types.--A hot-wire electrode ionizes the particles. In general, these sensors are sensitive primarily to the alkali metal content of the particles. Particles entrained in a gas flow impinge upon a hot wire, and if there are atoms or molecules within the particle of sufficiently low ionization potential, they will ionize at this heated electrode and be swept to a second electrode producing a current. The output current is proportional not only to the number of particles, but also to the alkali metal concentration of individual particles.

3. Optical smoke detectors.--These sensors respond to light that is either attenuated or scattered when particles enter a sensing volume that is illuminated by a light source such as an incandescent bulb or a light-emitting diode (LED). When the attenuation, or light extinction, method is used, an alarm is actuated if the normally present signal at a detector drops below some predetermined value. This type of detector relies upon a constant output from the light source. A slight accumulation of dust on the light source could decrease reliability considerably. For scattering-type devices, a detector sits off-axis of the illuminating light and responds only to light scattered from the particles into the view-field of the detector. The light-scattering method is generally more reliable than the attenuation method because the signal is measured above some zero background. For this type, the detector does not rely upon a constant output from the light source, and some built-in toleration exists for slight dust accumulation on the light source or for variations in the intensity of the source.

4. Ionization-type smoke detectors.--Radioactive material ionizes the air space between two electrodes. In the absence of particles, a steady-state current is established due to the ionization process. As particles enter this space between the electrodes, molecular air ions rapidly attach to them. These ions are then either lost from the system owing to feeble convective flows that carry the particles out of the system, or because the particles are much larger, their flux at the electrode surfaces is much lower than the

air ions by themselves. In actuality, it is probably the combined effects of these two actions that cause a reduction in the steady-state current. If the current loss is greater than some predetermined value, an alarm will signal the presence of a fire condition.

Optical and ionization-type smoke detectors offer some distinct advantages over other types of POC detectors. They are usually small and lightweight, capable of being battery operated, and inexpensive. Their sensitivity is high, but the harsh environmental conditions of the mine often render the devices insensitive or contribute to increasing the number of false alarms. High humidity and airborne dusts pose the most severe problems.

Recently, an ionization-type detector has been evaluated that is not severely affected by the dust or humidity. This has been achieved by using an intense radioactive source, which will tolerate considerable dust buildup. At the same time, the utilization of such a detector could present possible radiation hazards.

CURRENT RESEARCH

In the area of fire detector technology, the Bureau is involved in a continuing research program to evaluate and develop new sensors and new detection methodologies.

For over 10 years, the National Coal Board of Great Britain has used multipoint tube bundle sampling for the detection of spontaneous heatings in their coal mines. It is felt that this methodology has great potential for use in U.S. mines, especially in many of the Western seams where spontaneous combustion is a major problem. Other possible uses would include the monitoring of belt haulageways and the monitoring of stoppings or sealed areas. In addition, tube-bundle monitoring is being given serious consideration as a general fire detection method.[2] Through proper choice of tube diameter for a given length of tubing, transit times can be minimized, thus improving the overall response time of the system.

A major advantage of this method is that, instead of remotely locating detectors at each sampling point, a single station of more sensitive detectors, usually located above ground, can be used.

In the area of fire sensors, the Bureau of Mines has developed a prototype instrument that surpasses commercial sensors in terms of sensitivity, reliability, and portability. The Bureau instrument measures the concentrations of submicrometer particles liberated during all stages of the combustion process. In an earlier study,[3] an attempt was made to characterize some product of the combustion process that was common to all combustible materials. It was concluded that regardless of the combustible or the stage of the

[2]Hertzberg, M., and C. D. Litton. Pneumatic Fire Detection With Tube Bundles. J. Fire and Flammability, v. 9, April 1978, pp. 199-216.

[3]Hertzberg, M., C. D. Litton, and R. Garloff. Studies of Incipient Combustion and Its Detection. BuMines RI 8206, 1977, 19 pp.

combustion process, large concentrations of submicrometer particulates were always produced, and they were found to be the earliest product of the combustion process. Consequently, a program was initiated to develop a sensor that could measure the concentrations of these small particles, yet remain compact, portable, and inexpensive.

A more detailed description of the sensor and its operational characteristics is given by Litton and Hertzberg.[4] However, the following features are noteworthy: (1) possesses an internal rechargeable battery pack for up to 25 hours continuous dc operation; (2) contains a small internal pump, which continuously samples the air for particulates; (3) contains a cyclone and filter assembly for eliminating ambient dusts larger than 0.5 μm; (4) contains an analog output, which is directly proportional to the concentration of submicrometer particles; and (5) built-in logic circuitry for actuating an alarm once the alarm point has been set.

The logic circuitry uses an internal solid state timer to sample the analog signal every 2.5 sec. If the signal is above the alarm point for n successive sampling intervals, an alarm is given. The number of successive sampling intervals, n, is adjustable from 1 to 10. This type of temporal discrimination is designed to eliminate transient signals, which would cause false alarming.

In addition, the instrument has the capability to distinguish between particles of different sizes. This added capability provides additional means for discriminating against background signals, which would show up as false alarms. These instruments are currently available on a limited basis for field testing.

Other areas of current research activity include the development of a sensor for overheated rollers on conveyor belt systems, the development of a hazardous coal dust cloud monitor, investigation of sensing techniques for methane layering, and the continued evaluation and development of fire sensors.

CONCLUSIONS

Carbon monoxide and submicrometer particulate monitors offer the greatest potential for use as fire detectors. Research efforts by the Bureau and private industry, in cooperation with Mine Safety and Health Administration, U.S. Department of Labor, continue to improve the sensitivity and reliability of these products-of-combustion detectors. Improvements in thermal-sensing systems and in optical detection systems are continually being made. Practically any of the various types of detectors can be purchased commercially. Many have been modified so that they can be used underground; others are designed specifically for underground use.

[4]Litton, C. D., and M. Hertzberg. Principles of Ionization Smoke Detection. Development of a New Sensor for Combustion-Generated Submicrometer Particulates. BuMines RI 8242, 1977, 21 pp.

However, it is difficult to speak of fire detectors without a brief discussion of detection systems as a whole. Many systems are designed to protect key areas, such as belt haulageways, or for the continuous monitoring of unattended, high risk areas such as gobs or behind stoppings. Each of these systems provides limited area coverage and is essential to the fire protection plan for any mine. A total fire protection system would incorporate any number of these subsystems. The choice of detector, or detection methodology, for each subsystem would depend upon such variables as combustible loading within an area, ventilation patterns, maximum response times that could be tolerated, possible origin of fires, history of fire occurrences, etc. Since individual mines are essentially unique, the selection of appropriate detector hardware, and, more importantly, detection system, could vary drastically from mine to mine. Before any fire detection system is implemented, careful consideration should be given to the many factors involved in order to insure that the system provides adequate protection.

APPENDIX.--OUTLINE OF SENSORS

Thermal Sensors

Types..........	Thermocouple Thermoresistive Line-type Fixed temperature Rate-of-temperature rise
Applications...	Conveyor belt haulageways Large equipment protection Key-area coverage: (1) Transfer points, (2) loading stations, (3) shops, (4) flammable-liquid storage areas
Advantages.....	Rugged Low cost
Disadvantages..	Limited-area coverage Slow response Extensive network often required High maintenance

Aerodynamic Sensors

Types..........	Pressure transducers Fixed-pressure switches Rate-of-pressure rise Anemometers and velocimeters
Applications...	Explosion detection Flow reversals
Advantages.....	Fast response Low maintenance
Disadvantages..	Insensitive to fires

Optical Sensors

Types..........	Ultraviolet ($0.18\ \mu m < \lambda < 0.40\ \mu m$): Photoemissive Visible ($0.40\ \mu m < \lambda < 0.75\ \mu m$): (1) Photoemissive, (2) photovoltaic, (3) photoconductive Infrared ($0.75\ \mu m < \lambda < 20.0\ \mu m$): Photovoltaic and photoconductive
Applications...	Methane-air ignitions Dust explosions Large equipment protection Key-area coverage (see Thermal Sensor outline)
Advantages.....	Fast response Low maintenance
Disadvantages..	Limited-area coverage Generally insensitive to smoldering fires

Products-of-Combustion Sensors

Types..........	Gaseous products of combustion (CO, CO_2, hydrocarbons): (1) Chemical absorbents, (2) catalytic oxidation, (3) optical, (4) electrochemical, (5) semiconductor Submicrometer particulate products of combustion: (1) Condensation nuclei counters, (2) surface ionization, (3) optical smoke detectors, (4) ionization-type smoke detectors
Applications...	General fire protection Not intended for use as an explosion detector
Advantages.....	Responds to all stages of the combustion process High sensitivity Fewer detectors needed Portable Easily adapted to tube-bundle methodology
Disadvantages..	Maintenance often high Reliability low (but improving rapidly)

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